DYNAMIC ASSOCIATION OF EQUATIONS TO UNKNOWNS DURING SIMULATION OF SYSTEMS DESCRIBED BY HARDWARE DESCRIPTION LANGUAGES

RELATED APPLICATION DATA

This application claims priority from U.S. Provisional Application No. 60/139,985, filed June 18, 1999.

This application is related to co-pending U.S. Patent Application Serial No. _____, entitled "Classification of the Variables In a System of Simultaneous Equations Described By Hardware Description Languages," filed _____, which is incorporated herein by reference.

FIELD OF THE INVENTION

The present invention relates to the field of computer simulation of analog and mixed signal digital-analog physical circuits and systems, and more particularly to solving systems of simultaneous equations including dynamically changing equations.

BACKGROUND OF THE INVENTION

Simulation methods and apparatus are useful in increasing design productivity in a wide variety of applications because design defects can be detected prior to construction of the actual apparatus being simulated. Where the physical circuit or system includes an analog or mixed signal analog-digital component, simulation requires solving a system of simultaneous equations. The variables in these equations can be classified into one of several categories, depending on how their solutions are obtained. Input variables are variables whose values are effectively inputs to the system. Output variables are variables whose values are outputs of the system. Intermediate and system variables are variables that comprise the heart of the system, and whose values generally feedback on themselves.

In existing simulation systems, system variables exist in a one-to-one correspondence with some related equation; there is exactly one equation for each system variable slot. The relationship between a system variable and its related equation is determined prior to simulation and does not change during the simulation. Although this relationship is

desirable, it is not always achievable. Occasionally one or more of the equations in the system of simultaneous equations are dynamic: i.e., the specific equation changes depending on specific circumstances of the system of simultaneous equations. Standard techniques for solving systems of simultaneous equations break down in the presence of simulation time

5 changes in the relationship between equations and system variables.

Accordingly, a need exists for a technique for solving systems of simultaneous equations including conditional equations.

SUMMARY OF THE INVENTION

10 The simulator assembles a system of simultaneous equations. Equations that do not change depending on the circumstances are permanently associated with a system variable or slot. The conditions that apply to the conditional equations are evaluated. A conditional equation is active when the conditions related to the conditional equation evaluate to true. The active conditional equations are then assigned to slots in the system of simultaneous

15 equations, which can then be solved to determine the values of the system variables. If additional evaluations of the system of equations are required, the active conditional equations can be cleared from the slots, and a new set of active conditional equations selected.

The foregoing and other objects, features and advantages of the invention will become

20 more readily apparent from the following detailed description of a preferred embodiment, which proceeds with reference to the drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a flowchart of a method according to the invention for solving a system of

25 simultaneous equations representing a physical circuit or system including a conditional equation.

FIG. 2 is a flowchart of a method for selecting active conditional equations in the method of FIG. 1.

FIG. 3 is a flowchart of a method for verifying that the system of simultaneous

30 equations of FIG. 1 including active conditional equations is solvable.

FIG. 4 is a block diagram of a computer system implementing the method and apparatus of this invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Software systems that perform hardware simulation can do so using analog and discrete descriptions of the hardware behavior. Analog descriptions of the behavior are described as a set of simultaneous equations that need to be solved by a simultaneous equation solution algorithm in order to determine how the simulated system will behave. The simultaneous equations are expressed in terms of a certain number of unknowns and to find a solution there must be exactly one equation for each of the unknowns. The term "system variable" describes the set of unknowns within the set of equations. Simulation systems may decrease the size of the system of equations and the number of system variables by using techniques such as those described in U.S. Patent Application Serial No. _____, entitled "Classification of the Variables In a System of Simultaneous Equations Described By Hardware Description Languages," filed _____.

In analog designs, it is advantageous to be able to have equations that change during simulation in order to describe regions of operation for some device, a shown by a simple, illustrative example. Table 1 describes the behavior of a MOS transistor using conditions that describe the three regions of operation for the transistor. The example assumes:

1) there are electrical connections "drain," "source," and "gate";

2) vgs is the voltage from gate to source;

3) vds is the voltage from drain to source;

4) ids is the current through drain to source;

5) gm is the transconductance and vth is the voltage threshold of the transistor.

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Table 1

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if vgs-vth <= 0.0
     "ids == 0.0"                        is the active equation
else if vgs-vth <= vds
     "ids == 0.5*gm*(vgs-vth)**2"        is the active equation
else
     "ids == gm*((vgs-vth)-0.5*vds)*vds" is the active equation
end
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This system requires that the equations change during simulation as the model changes between the regions. This invention provides an efficient method for changing between the equations during simulation.

In a system of simultaneous equations, each system variable is said to have a "slot" and there is some set of equations that can be used to fill the slot in order to associate the system variable with an equation for solving the system of equations. The invention is a system and method that permits a simulation-time (i.e., dynamic) association between a set of

5   conditional equations and a set of system variable slots when the number of conditional equations is at least as large as the number of system variable slots. In this approach, the equation that fills the slot is not predetermined prior to simulation. Slots can be filled with different equations at different analog solution iterations during the simulation and an equation can populate different slots at different analog solution iterations during the

10   simulation. (An *analog solution iteration* is defined to occur when the analog solver requires that values need to be determined for the expressions forming the equations in the system.) This system and method is critical for high performance simulation of systems in which the set of active equations in the simultaneous system can change during the simulation. The language described in IEEE Standard 1076.1, subsequently referred to as VHDL-AMS, is a

15   hardware description language used for analog and digital simulation that permits such changes in the set of equations during simulation time and will be used as the context for describing the invention. The invention is not limited, however, to use in VHDL-AMS.

The dynamic association can be carried out as follows, using VHDL-AMS modeling terminology for illustrative purposes, in a simulator identified as VeriasHDL™.

20   VHDL-AMS defines the set of "characteristic expressions" that define the set of simultaneous equations the simulator must solve at a given analog solution iteration. (The term *characteristic expression* is defined in VHDL-AMS, and is subsumed by the more general term "conditional equation," also used in this document.) VHDL-AMS also defines "simultaneous if" and "simultaneous case" statements that permit the set of characteristic

25   expressions to change between analog solution iterations based on some specified condition. The conditions may involve values that change during simulation, which means that the system of simultaneous equations changes while the simulation is progressing. In order to deal with this problem, VeriasHDL defines a dynamic association of equations to system variables. Conditions can nest; a single equation or block of equations can have multiple

30   conditions controlling when the equation or block of equations become active; some of the conditions can also govern other equations and others not. The basic approach is as follows:

Assume that prior to simulation the system partitions the set of system variables (equation unknowns) into two subsets – unknowns with fixed associations to single

equations, and unknowns whose equation is selected dynamically from some set of potential conditional equations. One trivial choice is to have all system variables and equations participate in dynamic associations. In non-trivial cases, the analysis only needs to consider equations guarded by conditions whose values change during the simulation and the subset of

5   system variables that are not associated with any of the unguarded equations, but the selection of the set does not otherwise affect the applicability of dynamic association.

Assume that the partitioning results in a set of system variables $Q_1 \ldots Q_m$ and a set of conditional characteristic expressions $e_1, e_2, \ldots e_n$ existing inside simultaneous if and simultaneous case statements that will participate in the dynamic associations.

10   For each i from 1 to n, introduce a corresponding temporary variable, t_i, related to e_i and an assignment of the characteristic expression e_i to the temporary variable t_i. For each j from 1 to m, generate a new unconditional association between the slot for Q_j and a variable q'_j where q'_j is a new temporary variable that is otherwise undefined. Each q'_j is called the *dynamic slot target variable* for the associated Q_j.

15   During simulation, at a particular analog solution iteration, the active characteristic expressions are determined by evaluating the simultaneous if and case conditions. When a particular expression is determined to be active, say e_k, that expression is evaluated and a value is determined for the temporary variable t_k. The value of t_k is assigned to some q'_j, where j denotes some q' that has not yet been assigned a value in the current analog solution

20   iteration. A straightforward method for making this selection is to start j at 1 and to increment j after each dynamic association. This procedure effectively creates a new association between the slot for Q_j and the characteristic expression e_k and is then used for the current analog solution iteration.

Table 2 depicts an example situation in which e_k, e_{k+3}, and e_{k+8} are active and are

25   respectively associated with Q_j, Q_{j+1}, Q_{j+2}. The symbol "<->" indicates that the given dynamic slot target variable is associated with the slot for the indicated system variable.

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Table 2

$$
\begin{array}{lll}
\cdots & & ----- \; t_k \quad := \; e_k \\
& & \quad / \\
Q_j & <-> \; q'_j & <----- \; / \qquad\qquad \cdots \\
Q_{j+1} & <-> \; q'_{j+1} & <---------- \; t_{k+3} := e_{k+3} \\
Q_{j+2} & <-> \; q'_{j+2} & <----- \qquad\qquad \cdots \\
& & \quad\backslash \\
\cdots & & ----- \; t_{k+8} := e_{k+8} \\
& & \qquad\qquad\qquad \cdots
\end{array}
$$

At this point, preliminary values for the q'_j have been determined (through the values
for the t_k). The preliminary values for each q'_j and the fixed system variables can then be
substituted into the simultaneous equations to see if the system of simultaneous equations is

5   solved. If the values for the q'_j and the system variables do not solve the system of
simultaneous equations, the direction toward a solution is indicated, and the values for the q'_j
and the system variables can be perturbed until a solution for the system of simultaneous
equations is reached. How the system of simultaneous equations is solved is known in the
art, and will not be further described here.

10   The use of temporaries, $t_1 \ldots t_n$ is an implementation convenience. The temporaries t_1
$\ldots t_n$ can be replaced by a single temporary or register to move the value computed for a
characteristic expression directly into the selected q'.

During the associations, if all q' variables have been assigned a value and an
additional characteristic expression e_k becomes active, then an error has occurred in the

15   model since there are then too many equations for the number of unknowns. Similarly, after
all active characteristic expressions have been associated, if there are additional q' variables
that have not been associated, an error has occurred in the model since there are too many
unknowns for the number of equations.

In an alternative embodiment, the evaluated equation indices can be checked to

20   determine if any of the indices had been associated with system variable slots during the
previous analog solution iteration. If any active equations were associated previously with
system variable slots, associating the active equations with the same system variable slot as in
the previous iteration would improve convergence properties of the analog solution
algorithms due to having fewer trajectory changes in the system variables. Any new

25   equations can be associated with the remaining unassociated system variables in the
straightforward sequential manner.

FIG. 1 shows a flowchart of the method according to the invention for solving a system of simultaneous equations representing a physical circuit or system including a conditional equation. In FIG. 1, at step 105, the physical circuit or system is represented as a system of simultaneous equations. As discussed above, the system of simultaneous equations

5   can be reduced to only those equations associated with system variables. The system of simultaneous equations includes at least one slot for an equation with an associated condition (i.e. a conditional equation). At step 110, the conditions associated with the conditional equations are evaluated, and the active conditional equations (ACE) are determined. At step 115, the active conditional equations are associated with slots in the system of simultaneous

10 equations. This involves assigning the conditional equation to a dynamic slot target variable (DSTV). At step 120, the system of simultaneous equations is solved to determine the values of the system variables. At decision point 125, the method checks to see if there are any additional analog solution iterations needed for the simulation. If there are additional analog solution iterations needed for the simulation, the method returns to step 110, as shown by line

15 130. Otherwise, at step 135, the values for the system variables are used to validate the physical circuit or system.

FIG. 2 shows a flowchart of a method for selecting active conditional equations in the method of FIG. 1. FIG. 2 shows more detail of steps 110-120 of FIG. 1. At step 205, the conditions that apply to the conditional equations are evaluated to determine which of the

20 conditional equations are active. At step 210, the active conditional equations are selected. At step 215, each conditional equation is associated with the slot for a system variable. Finally, at step 220, solving the system of simultaneous equations determines values for the system variables.

FIG. 3 shows a flowchart of a method for verifying that the system of simultaneous

25 equations of FIG. 1 including active conditional equations is solvable. At step 305, the system of simultaneous equations is checked to make sure that no dynamic slot target variable is assigned the value of more than one active conditional equation. At step 310, the system of simultaneous equations is checked to make sure that each active conditional equation is assigned to at most one dynamic slot target variable. Finally, at step 315, the

30 system of simultaneous equations is checked to make sure that each dynamic slot target variable is assigned the value of an active conditional equation. If any of the checks 305-315 fail, then at step 320 an error condition is reported.

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FIG. 4 shows a computer system implementing the method and apparatus of this invention. In FIG. 4, computer system 405 includes a computer 410, a monitor 415, a keyboard 420, and a mouse 425. Other components may be part of the computer system 405, even though not shown in FIG. 4. For example, computer system 405 can include other

5   input/output devices, such as a plotting device. Similarly, devices such as monitor 415, keyboard 420, and mouse 425 can be missing from the computer system 405, provided that some input and output devices exist. Computer system 405 also includes simulator 430. Simulator 430 performs the simulation of analog and mixed signal digital-analog physical circuits and systems. Simulator 430 includes translation software 435, selection means 440,

10   assignment means 445, and solving means 450. Translation software 435 translates a hardware description language description of a physical circuit or system, such as HDL file 455, into the systems of equations. Selection means 440 is responsible for determining which conditional equations describing the physical circuit or system are active. Assignment means 445 is responsible for assigning the value of an active conditional equations to a dynamic slot

15   target variable in the system of simultaneous equations. Finally, solving means 450 is responsible for solving the system of simultaneous equations to determine values for system variable associated with the active conditional equations.

Having described and illustrated the principles of the invention in a preferred embodiment thereof, it should be apparent that the invention can be modified in arrangement

20   and detail without departing from such principles. We claim all modifications and variations coming within the spirit and scope of the following claims.

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